

*J. W. Rector III\**, Univ. of California, Berkeley (formerly Stanford Univ.); *S. K. Lazaratos*,  
*J. M. Harris*, and *M. Van Schaack*, Stanford Univ.

### SUMMARY

While crosswell traveltimes tomography can be used to image the subsurface between well pairs, the use of crosswell reflections is necessary to image at or below the base of wells, where the reservoir unit is often located. The extension from crosswell traveltimes tomography to crosswell reflection imaging is similar to the development of VSP, which grew out of the checkshot survey. Wavefield separation of direct and reflected arrivals in VSP is accomplished by dissecting the total wavefield into up and downgoing components. Since reflectors can exist both above and below the borehole source/receiver, wavefield separation of crosswell data into up and downgoing components does not achieve separation of direct and reflected arrivals. In our technique, we use multichannel filters applied in common source, common receiver and common offset domains to extract reflected arrivals from the complex total wavefield of crosswell data, which can contain mode conversions, head waves and complex multiples in addition to the simple direct and reflected arrivals. The multiple domains available for filtering and analysis make crosswell data more akin to multifold surface seismic data, which can also be filtered in multiple domains, rather than typical VSP data, where there is only one domain (common source) in which to filter. Wavefield separation of crosswell data is shown to be particularly effective against multiples when multichannel filters are applied in common offset space.

### INTRODUCTION

Recently, investigators have been attempting to use the reflection arrivals present in crosswell data to enhance and extend the imaged region between the two wells (Stewart, et al, 1991 and Lazaratos et al, 1991). The extension from crosswell tomography to crosswell reflection images is analogous to the development of vertical seismic profiling (VSP), which grew out of the checkshot survey (Hardage, 1985). Important reservoir zones at the base of the wells are illuminated by reflection.

To extract and image 'upgoing' reflected arrivals recorded in VSP data, a variety of signal processing techniques are used. A standard VSP processing sequence consists of wavefield separation, deconvolution, and mapping (Hardage, 1985). In wavefield separation, the moveout differences between the upgoing reflected arrivals and the downgoing transmission arrivals are used to dissect the total wavefield into the upgoing and downgoing components. Wavefield separation techniques distinguish between different arrivals based on moveout. In a VSP processing sequence, median filtering (Hardage, 1985) is often used to separate the total recorded wavefield into downgoing and upgoing arrivals, or equivalently, direct and reflected arrivals.

Multiples are attenuated through deconvolution of the upgoing wavefield using an operator derived from the downgoing wavefield (Anstey, 1980). The wavefield separated, deconvolved upgoing reflections are mapped from the domain of time versus depth to the domain of two-way time (or depth) versus borehole offset using a VSP-CDP transform (Wyatt and Wyatt, 1981) or a limited aperture migration (Van der Poel and Cassel, 1989).

A crosswell data set can be thought of as a series of 'offset' VSP's where source elevation varies and offset remains constant. VSP processing techniques can be used to extract and image crosswell reflection arrivals from each 'offset'

independently, stacking the data from different source elevations after mapping. However, crosswell data have several characteristics that are not present in conventional VSP. The presence of reflecting layers below and above the source and receiver as well as the wide angles (generally greater than 45 degrees) create new wave phenomena that require modifications to standard VSP wavefield separation techniques.

In this paper we describe a method by which crosswell data can be wavefield separated to extract reflection arrivals. The method exploits the multiple sorting domains available for crosswell surveys. Multichannel filtering of wavemodes in common offset space is found to be a particularly useful means to extract primary reflections from the complex total wavefield.

### CROSSWELL SHOOTING GEOMETRY AND STACKING CHART

In a typical shooting geometry for crosswell surveys, a receiver string of geophones, accelerometers or hydrophones is lowered into one well and a seismic source is lowered into another well. Common source or receiver 'fans' of data are recorded over a range of wireline depths. These fans typically cover rayangles, defined as the angle that a straight line forms between a source/receiver pair and the vertical, ranging from  $\pm 45$  degrees to 90 degrees. The crosswell data set can be sorted into (1) common source depth, (2) common receiver depth, (3) common midpoint, or (4) common offset gathers. These different gather types are analogous to the common shot, receiver, offset and midpoint gathers of surface reflection geometries except that wireline depth is the relevant independent variable rather than lateral position at the earth's surface. Figure 1 illustrates the raypaths taken by direct and upgoing reflections in the different domains. Using the terminology of Claerbout (1985), the vertical offset,  $h$ , is defined as  $g-s$ ; whereas the midpoint,  $y$ , is defined as  $(g+s)/2$ .

Although the analogy to surface seismic stacking charts is a useful one, reflections have very different representations in the crosswell geometry than they do in the surface seismic geometry. For example, in a region of zero dip, the surface seismic common midpoint is also a common reflection point (a CRP). In the crosswell geometry, the common midpoint (CMP) gathers contain reflections from many points between the source and receiver wells. A crosswell CMP gather does not correspond to a common reflection point. In fact, none of the four gathers are crosswell common reflection points.

In a homogeneous earth, the direct arrival moveout,  $M_d$ , between two adjacent traces can be written as:

$$M_d = (s-g)(\delta s/\delta z - \delta g/\delta z)/[(s-g)^2 + x^2]^{1/2} \alpha, \quad (1)$$

where  $\alpha$  is the P-wave velocity,  $\delta s/\delta z$  and  $\delta g/\delta z$  are the unitless source and receiver sampling intervals,  $x$  is the well-to-well separation (with the wells assumed to be vertical). For common receiver gathers  $\delta s/\delta z$  is non-zero and for common source gathers  $\delta g/\delta z$  is non-zero. For common offset gathers acquired with equal source and receiver sampling intervals,  $\delta s/\delta z = \delta g/\delta z$ , and the moveout of the direct arrival is zero. In common midpoint space acquired with equal sampling intervals,  $\delta s/\delta z = -\delta g/\delta z$ , and the direct arrival moveout is twice the moveout of the direct arrival in common source or receiver space.

The moveout of an arrival coming from a horizontal reflector in a homogeneous earth,  $M_r$ , can be written as:

$$M_r = (s+g-2z_r)(\delta s/\delta z + \delta g/\delta z)/[(s+g-2z_r)^2 + x^2]^{1/2}, \quad (2)$$

where  $z_r$  is the reflector depth. For upgoing reflections,  $s$  and  $g$  are less than  $z_r$  and for downgoing reflections,  $s$  and  $g$  are both greater than  $z_r$ . In common source or receiver space, the reflector moveout is hyperbolic, with the apex of the hyperbola approached as the source (or receiver) approaches the reflecting interface. In common offset space, a reflection arrival has roughly twice the moveout that it has in common source or receiver space; whereas in common midpoint space, the moveout of the reflection is zero provided source and receiver sampling intervals are equal.

#### SYNTHETIC MODELING OF CROSSWELL WAVEFIELDS

To illustrate the moveouts of some of the principal crosswell arrivals in the different gather domains, we created a synthetic data set from the simple earth model shown in Figure 2. Sources were positioned every 2 ft (.61m) between 312 ft (95m) and 406 ft (124m) and receivers were located every 2 ft (.61m) between 300 (95m) and 498 ft (152 m). Initially, an acoustic synthetic data set including all multiples was generated assuming an omnidirectional P-wave source radiation pattern with a 1,250 Hz Ricker wavelet and a receiver recording vertical displacement.

**Direct and Reflected Arrivals.** Figure 3 shows an example of a common source gather (CSG), a common receiver gather (CRG), and a common offset gather (COG). The data are displayed after normalizing each trace to the maximum amplitude in the 0 to 50ms time window. In Figure 3 we have labeled the P-wave direct arrival as well as upgoing and downgoing primary P-wave reflections. Linear moveout head wave arrivals crossing over the direct arrival can also be seen. As predicted by equation (1), the direct arrival path length and traveltime are roughly constant in the common offset gather. By contrast, the upgoing and downgoing reflections have moveouts in common offset space that are roughly twice the moveout of common source or receiver space. From Figure 3 it can also be observed that the wavefield becomes less 'complicated' as offset increases. This is a characteristic commonly observed in crosswell data. In some instances, the direct arrival cannot be identified at the near offsets.

For the purposes of wavefield separation, it is important to note that when the distance between source or receiver and the reflecting interface is large, the moveout of the reflected arrival becomes similar to the moveout of the direct arrival. This can also be seen from inspection of equations 1 and 2. Thus, moveout-based wavefield separation techniques applied only in common source or common receiver space will have difficulty in separating reflection arrivals from the direct arrivals for some trace depths.

The problem of crosswell direct and reflected arrival wavefield separation was noted by Pratt and Gouly (1991), who showed that common offset was a more optimal domain for separating direct and reflected wavefields than common source or common receiver space. When the data are sorted to the domain of vertical offset the direct arrival can be moveout distinguished from both the

upgoing and downgoing reflected arrivals for all depths. Rather than separating the arrivals based on incoming direction (i.e. upgoing versus downgoing) the offset domain distinguishes between different acoustic arrivals on the basis of *path length*. The raypath length of the direct arrival is roughly constant in a common vertical offset gather, and therefore traveltimes changes are related to vertical velocity variations rather than path length variations.

**Multiples.** One of the unique aspects of crosswell data is the ability to record downgoing as well as upgoing reflections. With two image perspectives on each interface (the interfaces intersected by the well are viewed from above and below), more quantitative impedance estimates should be possible. An attendant problem for crosswell wavefield separation is the presence of many interfaces below and above the source and receiver that can generate multiples.

Figure 4 is the acoustic synthetic of Figure 3 displayed with a 15 ms agc to enhance the weaker multiples. The weaker multiples can be distinguished from primary reflections because they terminate against a primary reflection, whereas primary reflections terminate against the direct arrival. A raypath for one of these multiples is depicted in Figure 5. Like primary reflections, multiples can be grouped into downgoing and upgoing types based on the raypath leg connecting the reflecting interface to the variable parameter (e.g. source or receiver). The moveout of this type of multiple,  $M_m$ , can be expressed (for a homogeneous earth) as:

$$M_m = [s-g+2(z_r-z_m)](\delta s/\delta z - \delta g/\delta z)/[(s-g+2(z_r-z_m))^2 + x^2]^{1/2}, \quad (3)$$

where  $z_m$  is the depth of the multiple-generating interface. Note that the depths  $z_r$  and  $z_m$  can be interchanged. In other words, the multiple can be viewed as coming from  $z_r$  and the primary can be viewed as coming from  $z_m$ . In a common source or receiver gather, upgoing multiples have a moveout that is similar to other upgoing arrivals (direct and primary reflected arrivals) and downgoing multiples have a moveout that is similar to other downgoing arrivals. Consequently, these multiples cannot be distinguished from primary reflections on the basis of moveout in common source or receiver space.

One way to separate multiples from primary reflections is to perform wavefield separation in common offset space rather than common source or receiver space. Note that in common offset space the multiples have nearly zero moveout, like the direct arrival. This can also be seen by inspection of equation (3). As mentioned previously, moveout-based wavefield separation in common offset space distinguishes between acoustic arrivals that have relatively constant path lengths and arrivals whose path lengths either increase or decrease. In the former category are direct arrivals and two bounce (and other even order bounce) multiples. In the latter category are primary reflections (with one bounce) and odd-bounce multiples.

To demonstrate the improved reflection image quality obtained when crosswell data are wavefield separated in common offset space, the model data were processed using two different processing flows. The first used conventional VSP wavefield separation applied in common source space, the second used wavefield separation applied in common offset space.

Figure 6 compares the mapped output of the two processing flows with the mapped primary reflection wavefield created by a geometric raytracing

algorithm. A single common source gather with a source depth of 386 ft (118 m) was used as input to the mapping. The downgoing reflections were mapped from the time and depth variables of crosswell acquisition space to image space with a VSP-CDP transformation (Wyatt and Wyatt, 1981) modified for the crosswell geometry. The data in Figure 6 are displayed in true depth (roughly a 1:1 scale) with a 30 ft agc applied. The data in the lower section appear to be lower frequency due to the data stretch similar to NMO stretch in the mapping process (Lazaratos et al., 1991). Note in Figure 6 that the continuity of the primary reflections is much better when the common offset wavefield separation is used. Also note that the horizontal arrivals above 210 ft in Figure 6c are multiple generated artifacts. These artifacts are substantially attenuated in the offset-processed section (Figure 6a).

### CONCLUSIONS

Crosswell full waveform data consist of a complex suite of arrivals. To extract primary reflections from the complex crosswell wavefield, enhancements to the conventional VSP wavefield separation process are necessary. Crosswell data can be sorted and processed in different domains such as common source, common receiver, and common offset. In this regard crosswell data is more like surface seismic data than VSP. By performing wavefield separation in multiple domains, primary P reflections can be extracted, potentially avoiding the added cost of multicomponent recordings. A synthetic example was used to illustrate the superiority of the proposed wavefield separation process as compared to the conventional VSP processing.

### ACKNOWLEDGEMENTS

This work was supported by the sponsors of the Stanford Tomography Project, the Gas Research Institute, and the David and Lucille Packard Foundation.

### REFERENCES

- Anstey, N. A., 1980, Seismic delineation of oil and gas reservoirs using borehole geophones: Gr. Brtn. Patents #1,569,581 and 1, 569,582.
- Claerbout, J., 1985, Imaging the earth's interior: Blackwell Scientific Publications.
- Hardage, B. A., 1981, An examination of tube wave noise in vertical seismic profile data: *Geophysics*, 46, 892-903.
- Hardage, B. A., 1985, Vertical seismic profiling Part A: Principles, 2nd edition, Pergamon Press.
- Heelan, P. A., 1953, Radiation from a cylindrical source of finite length: *Geophysics*, 18, 685-696.
- Lazaratos, S., Rector, J. W., Harris, J. M., and Van Shaack, M., 1991, High resolution imaging with crosswell reflection data: Presented at the 61st Ann. Internat. Mtg. Soc. Expl. Geophys., Expanded Abstracts, 1, 150-153.
- Pratt, R. G., and Goulty, N. R., 1991, Combining wave-equation imaging with traveltine tomography to form high resolution images from crosshole data: *Geophysics*, 56, 2, 208-225.
- Stewart, R. R., and Marchisio, G., 1991, Crosswell seismic imaging using reflections: Presented at the 61st Ann. Internat. Mtg. of SEG, Expanded Abstracts, 1, 375-378.
- Van der Poel, N. J. and Cassell, B. R., 1989, Borehole seismic surveys for fault delineation in the Dutch North Sea: *Geophysics*, 54, 1091-1101.
- Wyatt and Wyatt, 1981, Determination of subsurface structural information using the vertical seismic profile: Presented at the 51st Ann. Internat. Mtg. of Soc. Expl. Geophys., Dallas.

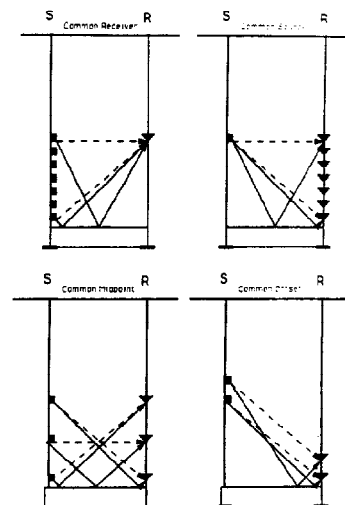


Figure 1: Raypath diagrams of direct and upgoing reflections in the different gather spaces. S is the source well and R is the receiver well.

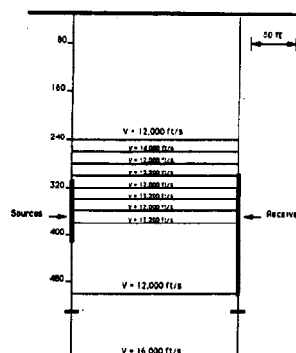
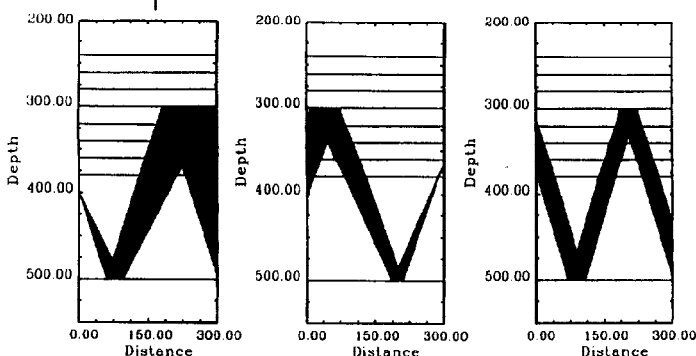


Figure 2: Geometry used to create synthetic crosswell data.

Figure 5: Raypaths taken by a crosswell multiple arrival.



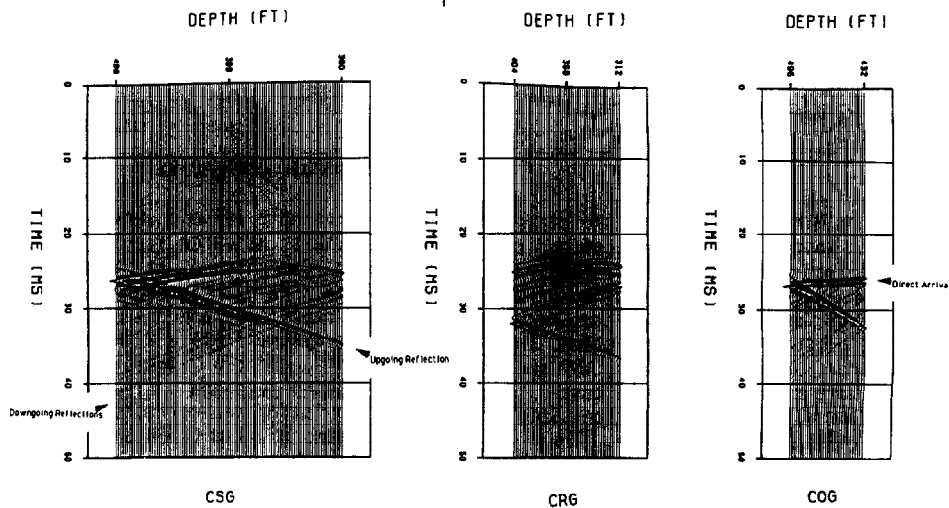


Figure 3: Acoustic synthetic crosswell gathers. CSG=common source gather, CRG=common receiver gather, COG=common offset gather.

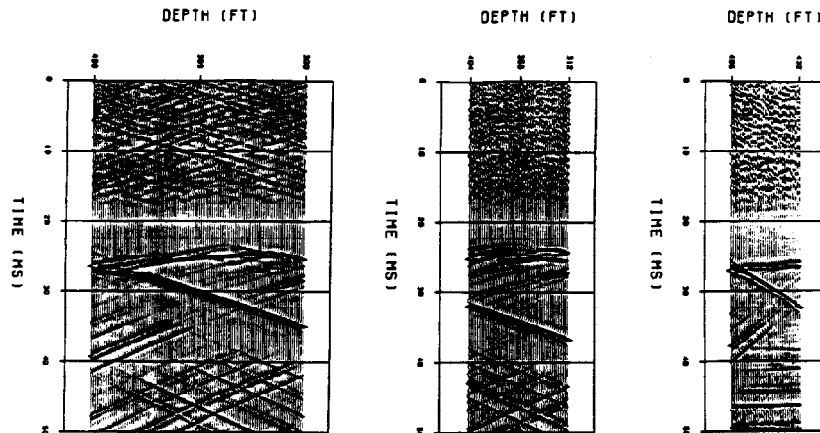


Figure 4: Data displayed with a 15 ms agc to enhance weaker multiples.

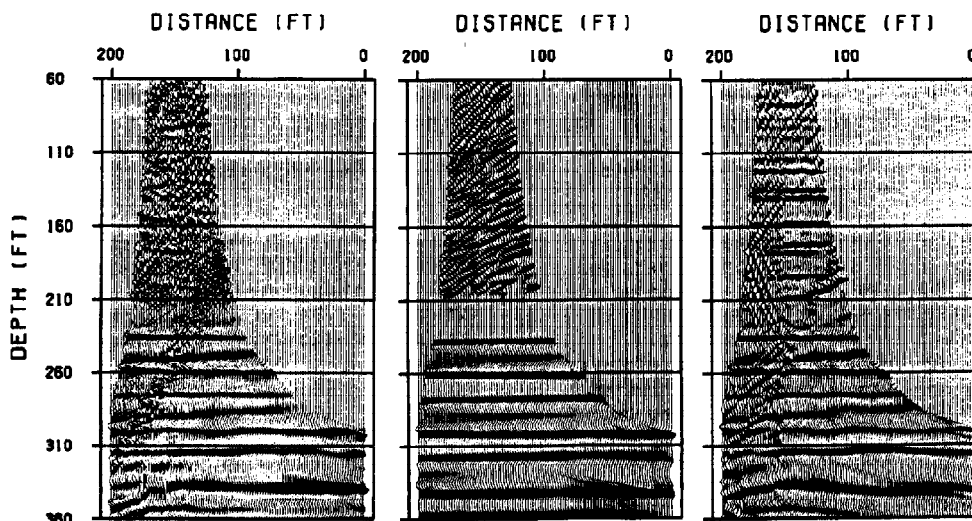


Figure 6: Imaged downgoing reflections (a) obtained from acoustic synthetic using VSP wavefield separation (b) modeled with geometric raytracer (c) obtained from acoustic synthetic using common offset based wavefield separation. The data have a 30 ft agc. Note that the VSP-processed data retain artifacts above 210 ft related to multiples and reflections are generally more broken.